

# Exclusive production of $\chi_c(0^+)$ meson and its measurement in the $\pi^+\pi^-$ channel

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## Abstract

We report on the results of a theoretical study of the central exclusive production of scalar  $\chi_c(0^+)$  meson via  $\chi_{c0} \rightarrow \pi^+\pi^-$  decay in high-energy hadron collisions at the RHIC, Tevatron and LHC. The corresponding amplitude for exclusive double-diffractive  $\chi_{c0}$  meson production was obtained within the  $k_t$ -factorization approach including virtualities of active gluons and the cross section is calculated with unintegrated gluon distribution functions (UGDFs) known from the literature. The four-body  $pp \rightarrow pp\pi^+\pi^-$  reaction constitutes an irreducible background to the exclusive  $\chi_{c0}$  meson production. We include the absorption effects due to proton-proton interaction and pion-pion rescattering. Several differential distributions for  $pp(\bar{p}) \rightarrow pp(\bar{p})\chi_{c0}$  process, including the absorptive corrections, were calculated. The influence of kinematical cuts on the signal-to-background ratio is investigated.

**Keywords:**  $\chi_c(0^+) \rightarrow \pi^+\pi^-$  decay, diffractive processes, two-pion continuum

## 1. Introduction

The mechanism of exclusive production of mesons at high energies became recently a very active field of research (see [1] and refs. therein). These reactions  $pp \rightarrow pMp$ , where  $M = \sigma, \rho^0, f_0(980), \phi, f_2(1270), f_0(1500), \chi_{c0}$ , provide a valuable tool to investigate in detail the properties of resonance states at high energies. The recent works concentrated on the production of  $\chi_c$  mesons (see e.g. Refs. [2–5]) where the QCD mechanism is similar to the exclusive production of the Higgs boson. Furthermore, the  $\chi_{c(0,2)}$  states are expected to annihilate via two-gluon processes into light mesons and may, therefore, allow the study of glueball production dynamics. The two-pion background to exclusive production of  $f_0(1500)$  [6] and  $\chi_{c0}$  [7] mesons was already discussed. In Ref. [8] a new perturbative mechanism of the  $\pi\pi$  production was discussed. Due to reasons ex-

plained in Ref. [8] this mechanism gives relatively small contribution in the  $\chi_{c0}$  invariant mass region.

The CDF Collaboration has measured the cross section of CEP  $\chi_c$  mesons in proton-antiproton collisions at the Tevatron [9]. In this experiment  $\chi_c$  mesons are identified via decay to the  $J/\psi + \gamma$  with  $J/\psi \rightarrow \mu^+\mu^-$  channel. The experimental invariant mass resolution was not sufficient to distinguish between scalar, axial and tensor  $\chi_c$ . While the branching fractions to this channel for axial and tensor mesons are large [10] ( $\mathcal{B} = (34.4 \pm 1.5)\%$  and  $\mathcal{B} = (19.5 \pm 0.8)\%$ , respectively) the branching fraction for the scalar meson is very small  $\mathcal{B} = (1.16 \pm 0.08)\%$  [10]. On the other hand, the cross section for exclusive  $\chi_{c0}$  production obtained within the  $k_t$ -factorization is much bigger than that for  $\chi_{c1}$  and  $\chi_{c2}$ . As a consequence, all  $\chi_c$  mesons give similar contributions [4] to the  $J/\psi + \gamma$  decay channel. Clearly, the measurement via decay to the  $J/\psi + \gamma$  channel cannot provide cross section for different  $\chi_c$ .

The  $\chi_{c0}$  meson decays into several two-body channels (e.g.  $\pi\pi, K^+K^-, p\bar{p}$ ) or four-body hadronic modes (e.g.  $\pi^+\pi^-\pi^+\pi^-, \pi^+\pi^-K^+K^-$ ). We have analyzed a possibility

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to measure  $\chi_{c0}$  via its decay into  $\pi^+\pi^-$  channel [7]. The branching fraction  $\mathcal{B}(\chi_{c0} \rightarrow \pi^+\pi^-) = (0.56 \pm 0.03)\%$  is large, the axial  $\chi_{c1}$  does not decay to the  $\pi\pi$  channel and  $\mathcal{B}(\chi_{c2} \rightarrow \pi^+\pi^-) = (0.16 \pm 0.01)\%$  is smaller [10]. In addition a much smaller cross section for  $\chi_{c2}$  production means that in practise only  $\chi_{c0}$  will contribute to the signal. The advantage of this channel is that the  $\pi^+\pi^-$  continuum has been studied recently [7, 11] and is relatively well known.

## 2. Signal and background amplitudes

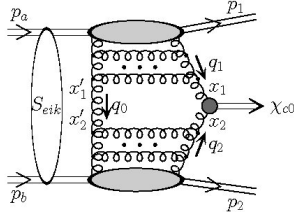


Figure 1: The QCD mechanism of exclusive diffractive production of  $\chi_{c0}$  meson including the absorptive correction.

The QCD mechanism for the diffractive production of heavy central system has been proposed by Khoze, Martin and Ryskin (KMR) and developed in collaboration with Kaidalov and Stirling for Higgs production (see e.g. Refs. [12]). In the framework of this approach the amplitude of the exclusive  $pp \rightarrow pp\chi_{c0}$  process is described by the diagram shown in Fig. 1, where the hard subprocess  $g^*g^* \rightarrow \chi_{c0}$  is initiated by the fusion of two off-shell gluons and the soft part is represented in terms of the off-diagonal unintegrated gluon distribution functions (UGDFs). The formalism used to calculate the exclusive  $\chi_{c0}$  meson production is explained in detail elsewhere [2].

The dominant mechanism of the exclusive production of  $\pi^+\pi^-$  pairs at high energies is sketched in Fig. 2. The expected non-resonant background can be modeled using a “non-perturbative” framework where the pion pair is produced by Pomeron-Pomeron fusion with an intermediate off-shell pion/Reggeon exchanged between the final-state particle pairs (see [7, 11, 13] for details). In calculations of the amplitude we follow the general rules of Pumplin and Henyey [14] used recently in Ref. [11] where a first estimate of the differential cross sections for the  $\pi^+\pi^-$  pairs production at the LHC energies has been presented. The Regge parametrization of the  $\pi^\pm p \rightarrow \pi^\pm p$  and  $\pi^+\pi^- \rightarrow \pi^+\pi^-$  scattering amplitude includes both Pomeron as well as  $f$  and

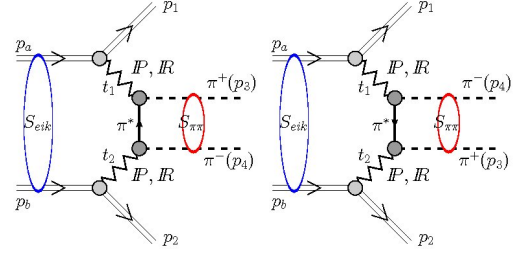


Figure 2: The double-diffractive mechanism of exclusive production of  $\pi^+\pi^-$  pairs including the pion and Regge exchanges, the absorptive corrections due to proton-proton interactions as well as pion-pion rescattering.

$\rho$  Reggeon exchanges with the parameters taken from the Donnachie-Landshoff analysis [15] of the total cross sections. The Regge-type interaction applies at higher energies and at low energies should be switched off (see [7, 11, 13]). In Ref. [7] we propose to use a generalized propagator. The form factors correct for the off-shellness of the intermediate pions are parametrized as  $F_\pi(\hat{t}/\hat{u}) = \exp\left(\frac{i/\hat{u} - m_\pi^2}{\Lambda_{off}^2}\right)$ , where the parameter  $\Lambda_{off}$  is obtained from fit to the experimental data [16] (see [7]).

## 3. Results

We first show (Fig. 3) the differential cross sections of  $\chi_{c0}$  CEP at  $\sqrt{s} = 14$  TeV without (dashed line) and with (solid line) absorptive corrections. These calculations were done with GJR NLO [17] collinear gluon distribution, to generate the KMR UGDFs, which allows to use low values of the internal gluon transverse momenta  $Q_t^2 \geq Q_{cut}^2 = 0.5 \text{ GeV}^2$ . The bigger the value of the cut-off parameter, the smaller the cross section (see Ref. [2]). In the calculations we take the value of the hard scale to be  $\mu^2 = M^2$ . The smaller  $\mu^2$ , the bigger the cross section [2]. In all cases the absorption effects lead to a damping of the cross section. In most cases the shape is almost unchanged. Exception is the distribution in proton transverse momentum where the absorption effects lead to a damping of the cross section at small proton  $p_t$  and an enhancement of the cross section at large proton  $p_t$ . In relative azimuthal angle distribution we observe a dip at  $\phi_{12} \sim \pi/2$ . Transverse momentum distribution of  $\chi_{c0}$  shows a small minimum at  $p_t \sim 2.5 \text{ GeV}$ . The main reason of its appearance is the functional dependence of matrix elements on its arguments [2].

In Fig. 4 we compare differential distributions of pions from the  $\chi_{c0}$  decay (see the peak at  $M_{\pi\pi} \simeq 3.4 \text{ GeV}$ )

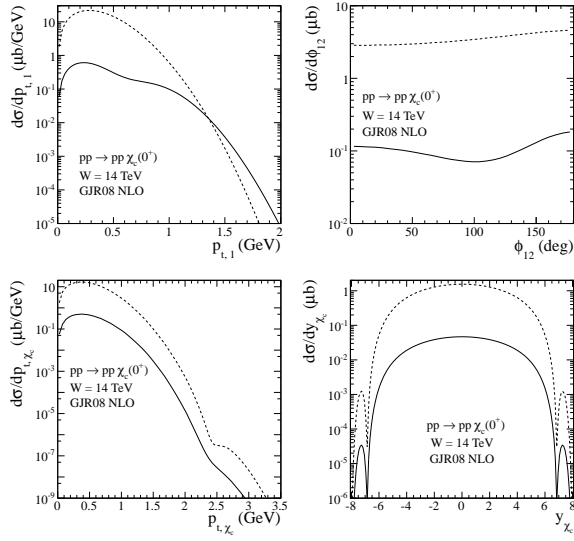


Figure 3: Differential cross sections for the  $pp \rightarrow pp\chi_{c0}$  reaction at  $\sqrt{s} = 14$  TeV without (dashed line) and with (solid line) absorption effects.

with those for the continuum pions. While left panels show the cross section integrated over the full phase space, the right panels show results including the relevant pion pseudorapidities restrictions  $-1 < \eta_{\pi^+}, \eta_{\pi^-} < 1$  (RHIC and Tevatron) and  $-2.5 < \eta_{\pi^+}, \eta_{\pi^-} < 2.5$  (LHC). The  $\chi_{c0}$  contribution is calculated with GRV94 NLO [18] and GJR08 NLO [17] collinear gluon distributions.

In Fig. 5 we show distributions in pion transverse momenta (left panels). The pions from the  $\chi_{c0}$  decay are placed at slightly larger transverse momenta. This can be therefore used to get rid of the bulk of the continuum by imposing an extra cut on the pion transverse momenta. In the right panels we show two-pion invariant mass distributions with additional cuts on both pion transverse momenta  $|p_{t,\pi}| > 1.5$  GeV. Now the signal-to-background ratio is somewhat improved especially at the Tevatron and LHC energies.

The main experimental task is to measure the distributions in the  $\chi_{c0}$  rapidity and transverse momentum. In Fig. 6 we show the two-dimensional ratio of the cross sections for the  $\chi_{c0}$  meson in its rapidity and transverse momentum:

$$\text{Ratio}(y, p_t) = \frac{d\sigma_{pp \rightarrow pp\chi_{c0}(\rightarrow \pi^+\pi^-)} / dy dp_t}{d\sigma_{pp \rightarrow pp\chi_{c0}} / dy dp_t}.$$

The numerator includes limitations on  $\eta_\pi$  and  $p_{t,\pi}$ . These distributions provide a fairly precise evaluation of the expected acceptances when experimental cuts are

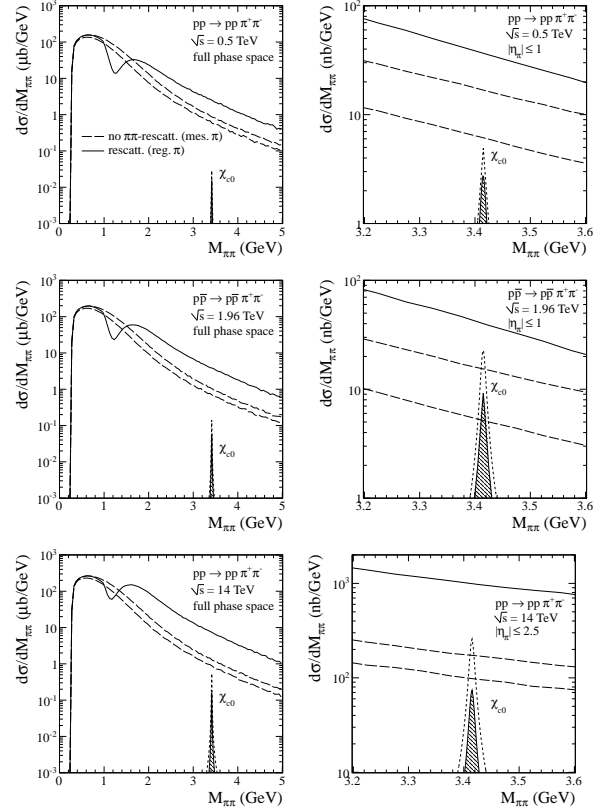


Figure 4: The  $\pi^+\pi^-$  invariant mass distribution at  $\sqrt{s} = 0.5, 1.96, 14$  TeV integrated over the full phase space (left panels) and with the detector limitations in  $\eta_\pi$  (right panels). Results for the  $\pi\pi$  continuum with the meson propagator and with the cut-off parameters  $\Lambda_{off}^2 = 1.6, 2$  GeV<sup>2</sup> (lower and upper dashed lines, respectively) as well as with the generalized pion propagator and  $\pi\pi$ -rescattering (solid line) are presented. We use GRV94 NLO (dotted lines) and GJR08 NLO (filled areas) collinear gluon distributions. The absorption effects both for the signal and background were included in the calculations.

imposed. The experimental data could be corrected by our two-dimensional acceptance function to recover the distributions of interest.

#### 4. Conclusions

It was realized recently that the measurement of exclusive production of  $\chi_c$  via decay in the  $J/\psi + \gamma$  channel cannot give production cross sections for different species of  $\chi_c$ . In this decay channel the contributions of  $\chi_c$  mesons with different spins are similar and experimental resolution is not sufficient to distinguish them.

We have analyzed a possibility to measure the exclusive production of  $\chi_{c0}$  meson in the proton-(anti)proton

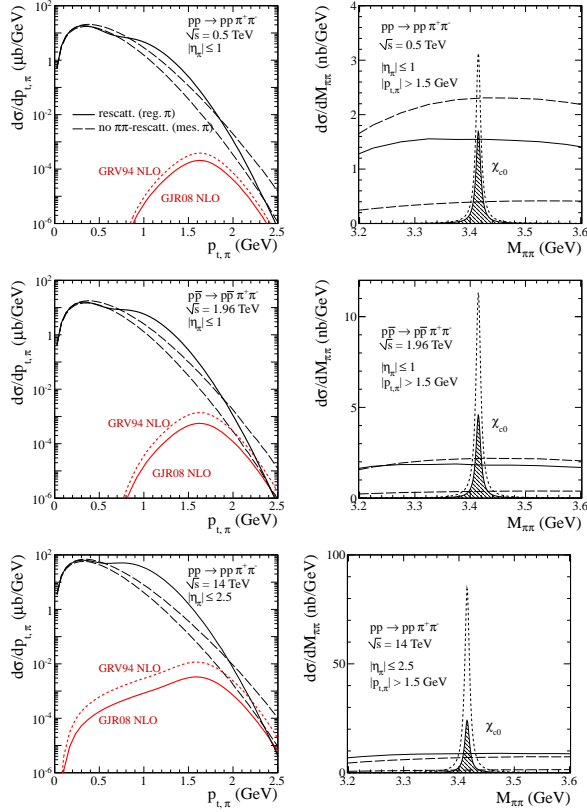


Figure 5: Left panels: Differential cross section  $d\sigma/dp_{t,\pi}$  at  $\sqrt{s} = 0.5, 1.96, 14$  TeV with cuts on the pion pseudorapidities. The absorption effects both for the signal and background were included in the calculations. Right panels: The  $\pi^+\pi^-$  invariant mass distribution with the relevant restrictions in the pion pseudorapidities and pion transverse momenta.

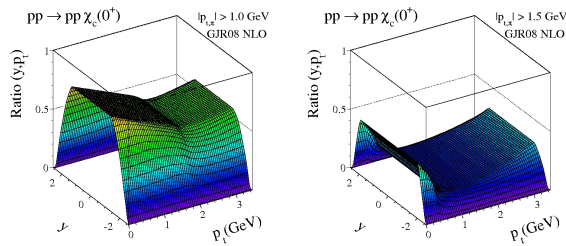


Figure 6: Ratio of the two-dimensional cross sections in  $(y, p_t)$  for the  $pp \rightarrow pp\chi_{c0}$  reaction with the relevant limitations on the pion pseudorapidities for the ATLAS or CMS detectors ( $|\eta_\pi| < 2.5$ ) and a cuts on the pion transverse momenta  $p_{t,\pi}$ .

collisions at the LHC, Tevatron and RHIC via  $\chi_{c0} \rightarrow \pi^+\pi^-$  decay channel. Since the cross section for exclusive  $\chi_{c0}$  production is much larger than that for  $\chi_{c1}$  and

$\chi_{c2}$  and the branching fraction to the  $\pi\pi$  channel for  $\chi_{c0}$  is larger than that for  $\chi_{c1}$  ( $\chi_{c1}$  does not decay into two pions) the two-pion channel should provide an useful information about the  $\chi_{c0}$  CEP.

We have performed detailed studies of several differential distributions and demonstrated how to impose extra cuts in order to improve the signal-to-background ratio. The two-pion background was calculated in a simple model with parameters adjusted to low energy data (see [7, 11]). We have shown that relevant measurements at Tevatron and LHC are possible. At RHIC the signal-to-background ratio is much worse but measurements should be possible as well. Imposing cuts distorts the original distributions for  $\chi_{c0}$  in rapidity and transverse momentum. We have demonstrated how to recover the original distributions and presented the correction functions for some typical experimental situations.

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